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VISCOSITY

Its Measurement and Relation to Fluid Friction

Viscosity, or fluid friction, is the property which retards the flow of all liquids and which is possessed by them in varying degrees. Sometimes this property is called loosely "body," "thickness" or even "weight." In selecting an oil for any specific purpose there are certain fundamental requirements which must be met regardless of those directly affecting bearing friction. For example, oils for turbine lubrication must not emulsify, must separate quickly from water and must not throw down objectionable deposits; ice machine oils must have low cold tests, and motor oils, low carbon residue.

When such requirements as these have been met for the particular service to which an oil is subjected, viscosity becomes the only one of all the physical properties normally called for in specifications of lubricating oils which has any direct bearing on their lubricating qualities, and is accordingly the property of paramount importance to all interested in lubrication; to the consumer who desires to secure the most efficient lubrication, and to the oil refiner who desires to maintain his products at a uniform standard.

In selecting the most suitable oil for any bearing, it is a well established custom to experiment with several oils of different viscosities and measure the rise in temperature due to the frictional heat of the bearing. That oil resulting in the least temperature rise is considered the best oil, all other factors being equal, because it indicates the least bearing friction. Oils of lower viscosity will cause greater bearing friction because they squeeze out and allow a more intimate contact between the moving parts, thus increasing the metallic friction and wear. The laws of this metallic friction are understood very imperfectly, and will not be dealt with in this article except to mention that there is some undefined property of an oil, sometimes called "unctuousness" or "oiliness," which has more to do with metallic friction than viscosity has. For example, animal and vegetable oils have much greater *oiliness* than mineral oils of similar viscosity and result in lower *metallic friction*. The oiliness of mineral oils, however, seems to increase with their viscosity, so that it is possible to secure the same oiliness as from a fatty oil, but only at a much higher viscosity.

An oil of higher viscosity than that producing the least heat, will also result in increased bearing friction, this time not because of metallic friction but because of the fluid friction of the oil itself, though there will be no increased wear. When a "perfect oil film" exists between moving surfaces so that

they do not touch, the bearing friction is due solely to the *fluid friction* of the oil film, in other words, its *viscosity*. In this case the property of oiliness just mentioned has nothing to do with the friction of the bearing, and a fatty oil will cause no lower losses than a mineral oil of the same viscosity.

Naturally, after the desired viscosity of some class of oil has been determined experimentally for some one instance, steps should be taken to assure uniformity in the viscosity of all subsequent shipments. This is accomplished by actually measuring the viscosity of the oil in an instrument known as a viscosimeter. In almost all cases the instrument used is of the so-called efflux type, in which the viscosity is measured arbitrarily by the time required for a certain quantity of oil to flow through a short tube of small diameter. There is a large number of well-known instruments of this type in use at present, particularly the Saybolt in the United States, the Redwood in Great Britain, and the Engler in Germany. The Barbey of France differs only in details such as measuring the quantity of flow per hour instead of the time for a given quantity. It will be appreciated that any one of these instruments will fulfill its mission of determining if different samples of oil tested have the same viscosity, but since the units are only arbitrary it is very difficult not only to compare the readings of instruments of one design with those of another, but even readings of instruments of the same design differing unavoidably in dimensions. This is, of course, a source of great inconvenience and confusion, and for this reason strenuous efforts are being made in this country to adopt some one type as a standard.

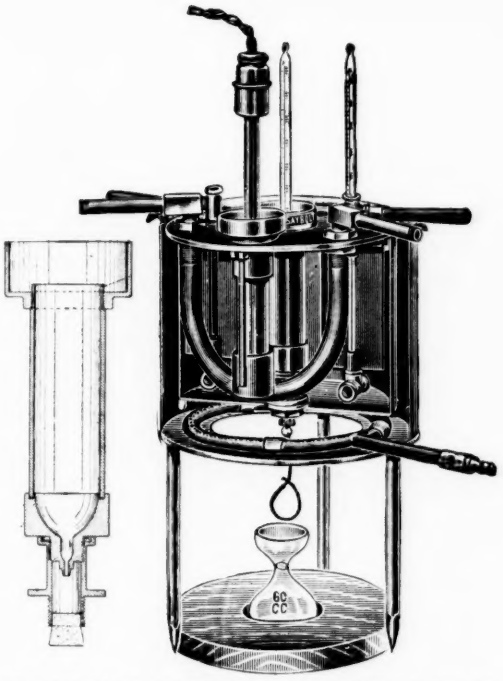
Because of its comparative simplicity, ease of operation and popularity, as well as for manufacturing reasons, the Saybolt Universal viscosimeter has been adopted by the American Society for Testing Materials and most American oil companies, and can be standardized by the United States Bureau of Standards. The Saybolt Universal viscosimeter is shown in the accompanying illustration. The tube contains about 70 cubic centimeters of oil when full, and the number of seconds required for 60 cubic centimeters of oil to flow through the outlet is arbitrarily called the viscosity in seconds Saybolt. The standardized dimensions of the outlet tube* are approximately 0.0695 inches in diameter, plus or minus 6/10000 inches, and 0.483 inches long, plus or minus 4/1000 inches. It is evident that this is a very simple instrument, with no mechanical moving parts to get out of order or adjustment, and one which requires but little skill to operate.

Thus it may be seen that a simple and convenient laboratory test is available for all practical requirements of both oil refiners and oil users to assist in maintaining unvarying lubricating properties of oils in service. The readings of this instrument are affected directly by the fluid friction of the oils tested, and these indirectly indicate the oiliness of any one class of oils. Without some such means of doing this it would probably be impossible for an oil refiner to supply his customers twice with the same grade of oil.

In addition to serving as a means of checking the uniformity of various lots of oils, there are certain technical aspects of viscosity which are sometimes necessary in analytical engineering work, where the relationship between fluid friction and bearing friction should be understood in order to estimate in advance of experimental work the effect of various design changes. For this reason the nature of fluid friction will next be analyzed and then its action in a Saybolt viscosimeter will be taken up.

Experimental evidence indicates that under conditions experienced between flat lubricated surfaces** the oil flows in parallel layers much like a pack of playing cards sliding over each other, the outside layers adhering to the surfaces and not sliding with respect to them.*** The resistance of these layers to sliding past each other is due to the fluid friction or so-called absolute viscosity of the oil. On this assumption of parallel flow is based the measurement of absolute viscosity, which is defined as the force in dynes necessary to move each square centimeter of metal surface at a velocity of

* Bureau of Standards, Technologic Paper No, 112, p. 7
** Archbutt & Deeley, p. 16-17, 23.
*** Archbutt & Deeley, p 24.



THE SAYBOLT UNIVERSAL VISCOSIMETER IN SECTION SHOWING THE THREE METHODS OF HEATING THE BATH; ELECTRICITY, GAS, OR STEAM, AND THE TWO PADDLES FOR AGITATING THE BATH. ON THE LEFT IS SHOWN A CROSS SECTION OF THE EFFLUX TUBE ITSELF TO A LARGER SCALE.

one centimeter per second if the distance between the surfaces is one centimeter. Using English units, this may be expressed in the following formula:—

$$\left(\begin{matrix}\text{Force of}\\ \text{fluid friction}\\ \text{in pounds}\end{matrix}\right) = \frac{\left(\begin{matrix}\text{Absolute}\\ \text{viscosity}\\ \text{in poises}\end{matrix}\right) \times \left(\begin{matrix}\text{Areas}\\ \text{in}\\ \text{sq.ins.}\end{matrix}\right) \times \left(\begin{matrix}\text{Velocity}\\ \text{in}\\ \text{ft./sec.}\end{matrix}\right)}{5760 \times \left(\begin{matrix}\text{Thickness}\\ \text{of oil film}\\ \text{in inches}\end{matrix}\right)} \quad \text{I.}$$

These units of absolute viscosity are known as "poises"* and it so happens that the viscosity of water at 20.2 degrees C. (68.4 degrees F.) is exactly 1/100 poises. Accordingly a unit one hundredth as large is customarily used and is called the "centipoise"** (abbreviated cp). Then the absolute viscosity of water at 20.2 degrees C. becomes exactly 1.0 cp. and the viscosities of all other substances expressed in this unit will show their relative viscosities when compared with water.

For a cylindrical bearing this formula may be rewritten;

$$\text{Torque of fluid friction in foot pounds} = \frac{\left(\begin{matrix}\text{Absolute}\\ \text{viscosity in}\\ \text{centipoises}\end{matrix}\right) \times \left(\begin{matrix}\text{Shaft}\\ \text{diameter}\\ \text{in inches}\end{matrix}\right)^3 \times \left(\begin{matrix}\text{Bearing}\\ \text{length}\\ \text{in inches}\end{matrix}\right) \times \text{R. P. M.}}{505{,}000{,}000 \times \left(\begin{matrix}\text{Clearance}\\ \text{on diameter}\\ \text{in inches}\end{matrix}\right)} \quad \text{II.}$$

* Bureau of Standards, Technologic Paper, No. 100, p. 5.
** Bureau of Standards, Scientific Paper, No. 298, p. 72.

This formula emphasizes a fact often overlooked that *increased bearing clearances reduce fluid friction.*

Hence it follows that any perfectly lubricated bearing in which there is no metallic contact, such as those of spinning machine spindles, turbine bearings and similar high speed bearings running in an oil bath, may be considered as a sort of absolute viscosimeter, in which the only two variables are bearing friction and the absolute viscosity of the oil at the temperature in the bearing; where one is known the other may be found quickly by computation. It must not be overlooked, however, that the accurate measurement of so small a dimension as the clearance is not a simple task, and the use of the above equation can be no more accurate than this measurement.

With these thoughts of the flow of oil in parallel layers and the resulting fluid friction in mind, it is now possible to analyze the behavior of an oil in an efflux viscosimeter, and show how its readings will correspond to or deviate from absolute viscosity. In these instruments the potential energy resulting from the weight of the oil above the outlet tube is absorbed both in overcoming the fluid friction of the oil in the small outlet tube, and in giving the oil stream velocity or momentum. Hence the time taken for a given quantity of oil to flow will vary with the specific gravity of the oil because of the different weight of the oil and the different amounts of energy which are consequently available to produce the flow. Saybolt readings thus involve absolute viscosity modified by the specific gravity. For example, an asphaltic-base oil of 20 degrees Be. gravity having the same viscosity Saybolt as a 30 degree Be. paraffine-base oil at some one temperature, will in reality have about 7 per cent. greater absolute viscosity at that temperature. Changes in temperature also affect the gravity considerably, a 20 degree Be. oil at 60 degrees F. becoming about 35 degrees Be. at 300 degrees F.

The amount of energy absorbed in producing velocity increases rapidly with the velocity, leaving less available for overcoming

fluid friction. Saybolt readings, for this reason, do not decrease for low viscosities as rapidly as the absolute viscosity of the oil tested. The following formula will show the relation between absolute viscosity, Saybolt readings, and the velocity correction, for a Saybolt instrument of exactly correct dimensions:

$$\frac{\text{Absolute viscosity}}{\text{Specific gravity}} = \text{Kinematic vis.: cp.}$$

$$= 0.22 \times \text{Say. vis.} - \frac{180}{\text{Say. vis.}} \qquad \text{III.}$$

As mentioned previously, it is necessary to know the specific gravity of the oil at the temperature of the viscosity reading, in order to correct Saybolt readings to absolute viscosity. These data are not always available however, and consequently involve additional experimental work. Frequently, however, it is possible to use a short cut and dispense with these data, as when comparing one oil in different efflux viscosimeters, or different oils of approximately the same gravity. In this case the term "Kinematic viscosity" is used which, as can be seen from the equation, is simply the absolute viscosity uncorrected for specific gravity.

The last term of the right-hand side of the equation has no other meaning than to make correction for the velocity of the oil, and may be ignored for Saybolt readings greater than 200 seconds without introducing an error greater than 2 per cent., in which case;

$$\text{Kinematic vis. cp.} = 0.22 \times \text{Say. vis.} \qquad \text{IV.}$$

For lower viscosities than 200 seconds the correction increases rapidly until it is 91 per cent. for 30 seconds. In other words, only 9 per cent. of the energy causing flow is available for overcoming fluid friction. This is the reason for the very erroneous impression entertained by many that at high temperatures all oils have nearly the same viscosity. For example, the viscosity, Saybolt, of water varies from 30.2 seconds at 100 degrees F. to 29.3 seconds at 210 degrees F. This is an apparent difference of only 3 per cent. while in reality there is a true or absolute viscosity difference of over 137 per cent. which also means a difference of fluid friction in a bearing of 137 per cent.

Standardization of the Saybolt Viscosimeter

The constants for equation III vary for different dimensions of the outlet tube. If this fact is ignored, errors will result because of the variation of the dimensions resulting from the permissible manufacturing inaccuracies. These errors may amount to as much as 7 per cent. for readings above 60 seconds Saybolt, but they may be much greater for lower readings, being plus 16 per cent. and minus 24 per cent. for 35 seconds Saybolt. It is, accordingly, necessary when important or accurate work is to be done with one of these instruments to standardize it, that is, determine its true equation. This may be done either by experiment with two or more fluids of known viscosity, or by resorting to the theory of parallel flow and calculating the equation from the actual measurements of the instrument.* The accuracy with which these two methods check each other is one of the strong proofs of the theory of parallel flow referred to previously. By calculation from the extreme limits allowed in the dimensions of the standard tube, the maximum variation of the first constant of equations III and IV was found to be from 0.204 to 0.234, and that of the second constant of equation III, from 179 to 182.**

By either of these methods of calibration, the equation for any other type of similar efflux instrument may be determined. From such equations, the curves of Chart I have been plotted in order to assist in converting readings of various well-known viscosimeters to absolute. By their use it is a simple matter to convert readings from one viscosimeter to another. They are practically self-explanatory, but an example may make their use clearer.

Problem;

(a) What is the absolute viscosity of an oil of 2.5 degrees Engler viscosity?

(b) What is the corresponding Saybolt reading for this oil?

Solution;

* Archbutt & Deeley, p. 21, 22.
Bureau of Standards, Technologic Paper No. 100, p. 6
** Bureau of Standards, Technologic Paper No. 112, p. 20.

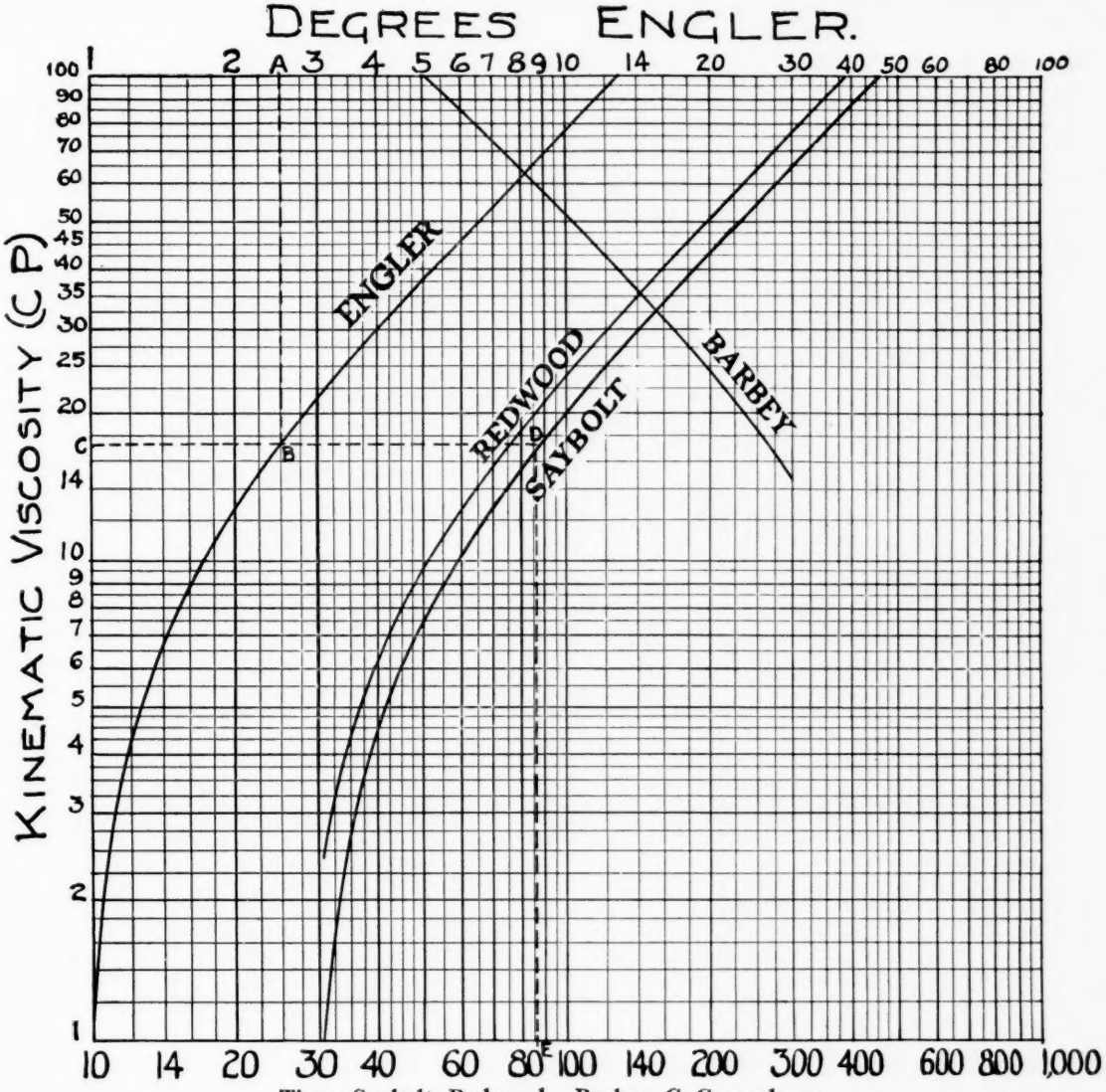


CHART 1

(a) Follow down the vertical line from 2.5 degrees Engler (Point A) until it intersects the curve "Engler" at "B," and then follow horizontally to the left-hand scale which shows a kinematic viscosity of 17.2 cp. at "C." Multiply by the specific gravity of this oil at the temperature occurring when the 2.5 degrees was originally read to get absolute viscosity.

(b) From point "B" follow horizontally to the right until the Saybolt curve at "D" is intersected, then follow down vertically and read 86 seconds on the Saybolt scale at "E."

Temperature Effects

All oils as well as other fluids lose their viscosity as their temperatures rise. This is a matter of great importance in connection with the performance of an oil in a machine, for the magnitude of fluid friction is dependent on the viscosity at the temperature of the oil in use and no other temperature. For obvious manufacturing reasons oil refiners standardize the viscosity of their products at 100 degrees F. for low-viscosity oils and 210 degrees F. for high-viscosity oils, and when it is desired to know the viscosity at the service temperature much experimental data may be elimi-

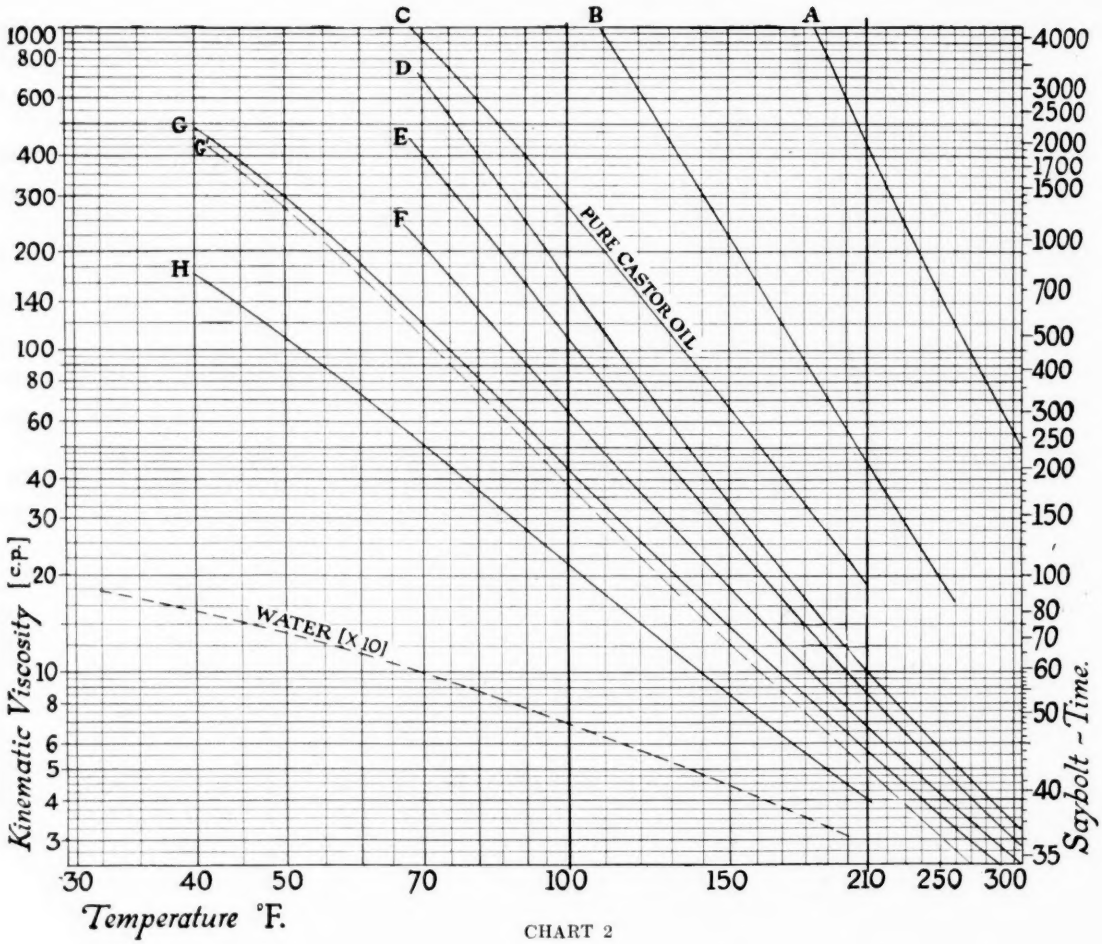


CHART 2

nated by the use of curves showing the relation between viscosity and temperature. Ordinarily these curves are plotted to scales with equal divisions along their length, but such curves are not very satisfactory because if they are made to a scale small enough to show the viscosities at low temperatures, the readings at high temperatures will be so small that they cannot be read with any degree of accuracy. Furthermore, the points for any one oil lie on a line of very pronounced curvature so that it is not possible to draw it with accuracy without quite a number of points, nor to estimate other points lying beyond the limits of the curves. One way of getting around this difficulty is to show the changes of "fluidity," instead of viscosity, with temperature, fluidity being defined as 1 ÷ viscosity, in other words, the reciprocal of viscosity. These curves are almost straight lines for the higher temperatures, but the higher-viscosity readings (or the lower-fluidity readings) are so close together that they cannot be read satisfactorily. Also the term fluidity is not so commonly used and understood by those who use oils as the term viscosity.

The most satisfactory way of all for showing graphically the relation between viscosity and temperature is to resort to logarithmic scales, as is done in Chart 2. Errors in reading are almost constant in percentage rather than amount, and a wide range of readings can therefore be presented satisfactorily on a single sheet. Also the curves are so nearly straight lines that only two or three points are required in order to estimate all others. This is of course, a coincidence, because there is no fundamental reason why the temperature should be in terms of a purely arbitrary

scale such as Fahrenheit, but it is very convenient.

These curves show the variation of kinematic viscosity with temperature for several well-known mineral oils, ranging from a spindle oil to a very heavy gear oil. For oil G a curve G′ showing absolute viscosity to the same scale as kinematic is given, indicating the variation resulting from gravity corrections. A scale at the right gives equivalent Saybolt readings. Oils from different crudes will have different slopes, hence a refinery making up an oil of a given specification from different crudes cannot be tied to specifications at more than one temperature.

As a matter of interest curves are shown for pure vegetable castor oil* and for water**, the latter being shown to a scale of kinematic viscosity ten times as great in order to get it on the sheet. It is shown because it is not commonly realized that the viscosity of water changes with temperature just like that of oils, and that at 32 degrees its absolute viscosity is about 6¼ times as great as at 210 degrees.

Conclusions

In this article, it has been shown that an efflux type of viscosimeter offers a very simple and satisfactory means of assisting refiners in maintaining the lubricating qualities of their products uniform, and users in identifying those oils which they have learned from experience will give them satisfactory service. It is, of course, highly desirable when using instruments giving arbitrary rather than true readings of viscosity for commercial purposes, to have as few different arbitrary scales as possible. Hence it is greatly desired that one type be adopted as standard, so that readings of an oil will be the same for all instruments. The Bureau of Standards at Washington has done excellent work in standardizing the Saybolt instrument which will be of great benefit to engineers and oil men throughout the country.

There are, however, instances where technical investigations make it necessary to calculate in advance the amount of power lost in bearing friction or in pumping oil through pipes, etc. These should be handled by using absolute viscosity. But once the desired information is secured by the use of absolute readings, then by the use of conversion charts the results may be referred to Saybolt Universal viscosity. Thus for practical purposes of standardization and checking the Saybolt viscosimeter may be used, thereby taking advantage of the wide-spread use of this simple and easily used instrument. Consequently, for commercial use, this instrument is as its name implies, universal in its application.

* Bureau of Standards, Technologic Paper No. 112, p. 24, 25.
** Bureau of Standards, Scientific Paper No. 298, p. 75.

Flow of Oil Through Pipes

In the transportation of crude petroleum or its liquid products, no step is of more importance than the pumping of them through pipes, and while the subject has been given much thought and study, it is of such a complicated nature and so many conditions affect it, that no definite law or formula has as yet been devised to cover completely all of its phases. In order to establish a law of flow a large number of experiments have been carried on at various times and considerable information has been accumulated. Some of this appears of sufficient value to warrant us giving our readers the benefit of it as far as it goes although it may not be complete and is subject to revision.

It has been proved to the satisfaction of most investigators that viscous fluids when flowing through a pipe or similar conduit follow one of two general conditions. These may be described as "stream line flow" and "turbulent flow." In the first the liquid seems to pass through the pipe in a manner similar to the movement of a large number of concentric tubes, those at the center having the greatest velocity and those near the surface of the pipe the least. In the second case the oil acts more like a great number of

small spheres which roll over each other as they pass through the pipe and constantly change their relative positions both longitudinally and transversely.

Whether the liquid is flowing in accordance with the first or second condition depends upon its velocity, its viscosity, the diameter of the pipe and its internal condition. At the lower range of velocities the first condition holds true, while at higher velocities the second applies. The point at which the flow passes from one condition to the other is known as the "critical velocity" the value of which has been found to decrease as the viscosity decreases and as the pipe diameter increases. From these statements it might be assumed that the critical velocity for a given fluid flowing in a given size pipe is a definite quantity, but such, unfortunately, is not the case as there exist what might be defined as high and low values. This phenomenon seems to be due to the fact that both conditions tend to continue when once started, thus as the velocity is increased, turbulent flow begins at a higher point than that at which stream line flow starts when the velocity is decreased after turbulent flow has existed. This range is appreciable and while little is known about it, some tests have shown a variation of more than ten per cent. under and over the average.

In analyzing the different factors that affect the flow of fluids, parallels may be drawn to the behavior of solids sliding upon one another, and while the same general formulae may apply, certain constants must be introduced which can only be determined experimentally.

The factors that seem to affect the force necessary to cause flow may be enumerated as follows:—

(a) Velocity of the fluid
(b) Diameter of the pipe
(c) Length of the pipe
(d) Surface condition of the pipe
(e) Absolute (*) viscosity of the liquid

A liquid flowing at a definite velocity through a level pipe would continue at that velocity, except for the resistance offered by the friction between the two. It should be remembered that the force of adhesion of an oil to metal is greater than the force of cohesion between the different particles of oil, therefore, when an oil is moving with respect to a smooth metal surface, this surface will at all times be coated with a film of the oil, and the movement will actually be that of one surface of oil with respect to another. This, by definition, when reduced to unit quantities is "absolute viscosity." Of course, if the unevenness of the metal surface is greater than the thickness of the oil film, a true sliding of one oil surface over another will not exist.

It has been proved both experimentally and mathematically that liquids, when flowing through small tubes, follow the law expressed by the formula

$$P = K \frac{\text{Vel.} \times \text{Vis.} \times L}{D^2} \qquad \text{I.}$$

In which P is the unit pressure, Vel. the unit velocity, Vis. the unit viscosity, L the total length of the pipe, D the diameter of the pipe and K a constant varying with the system of units used.

This is known as Poisseuille's formula and when applied to water takes the form

$$h = \frac{V \times L}{C \times D^2} \left(\frac{60}{t + 10} \right) \qquad \text{II.}$$

In this formula h is the pressure head in feet, V the velocity in feet per sec., L the length of the pipe in feet, D the diameter of the pipe in inches, t the temperature of the water in degrees F. and C a constant depending on the kind of pipe—about 500.

As the factor $60/(t+10)$ when plotted against the absolute viscosity of water gives very nearly a straight line, absolute viscosity may then be substituted for this factor and with a suitable change in the constant formula II becomes the same as I and will hold for any fluid.

As soon as the velocity exceeds the critical point, a marked change in the pressure required is noted and while the different factors in formula I continue to affect it, they do not do so at the same rate.

It follows, therefore, that a formula that will apply to those velocities above the critical will take the form of

$$P = K \frac{\text{Vel.}^m \times \text{Vis.}^n \times L}{\text{Dia.}^p} \qquad \text{III.}$$

It is necessary to determine the values of m, n, p and K from work that has been done

* For definitions of viscosities and the methods used in converting the several kinds now used in practice to absolute, the reader's attention is directed to the article on this subject on page 1

or by new experiments before this formula can be used wth safety.

As stated before, the point at which critical velocity takes place cannot be definitely determined but a formula offered by Poisseuille and developed by Reynolds seems to be the best. This is as follows:

$$V = \frac{R \times Vis.}{Den. \times D} \qquad IV.$$

In which V is the velocity in cm. per sec., Vis. the absolute viscosity in dynes—sec per sq.cm., Den. the density in grams per cu.cm., D the diameter in cm., and R the constant known as Reynolds' number.

The value of R has been investigated by many experimenters but, unfortunately, most of them have determined it for water or other similar liquids and not for viscous fluids like oils. It has been assumed that R is a constant for a fluid, but some excellent work done by A. C. Preston and reported in the Journal of Engineering, University of Colorado, December, 1915 seems to show that R decreases as the absolute viscosity increases, having the following approximate values:—

Abs. Vis.	R
0.025	1400
0.400	950
0.810	700
1.07	620

These, however, have not been sufficiently checked by other investigators to warrant their use except for very general estimating. It is necessary that a very careful study be made of the subject of critical velocity before the broader problem of flow through pipes can be satisfactorily solved.

In the determination of m, n, p and K used in formula III articles by the following authors have been reviewed:—

A. M. Hunt
S. D. Carothers
A. C. Preston
And many others.

In these reports much good material is given but unfortunately all of them cover a very small range either in pipe size, viscosity or velocity of flow and so a comparison of results is not possible.

The values of the exponent of the velocity, as derived from the above articles, vary from 1.85 to 1.5 with the decrease taking place as the viscosity increases. It is believed, however, that a value of 1.75 will cover most conditions satisfactorily. The variation in the exponent of the diameter was much smaller as the range was only from 1.2 to 1.3 with an average of 1.25. The effect that the viscosity has upon the required pressure shows the greatest lack of uniformity of any of the factors and while one author seems to think that the effect varies as the first power, he is not checked by any of the others. A value of the viscosity exponent that seems to meet the best average is about 0.45. Therefore, formula III will take the following form when the previously determined factors are introduced:—

$$P = \frac{Vel.^{1.75} \times Vis.^{0.45} \times L}{C \times Dia.^{1.25}} \qquad V.$$

Here P is the pressure in pounds per sq. in., Vel. the velocity in feet per sec., Vis. the absolute viscosity in dynes—sec. per sq. cm., L the length of the pipe in feet and Dia. the diameter of the pipe in inches. The value of C depends upon the units used and other modifying conditions but will be in the neighborhood of 90 for the more viscous oils and for the larger pipe diameters.

In considering the application of formula I to the flow of oil through relatively large size pipes at those velocities below the critical point, it should be borne in mind that this formula was developed from experiments made upon tubes of small size and of such material that the inner surfaces were much smoother than commercial piping, therefore, it cannot be expected that the pressure required will vary directly as the first powers of the velocity and viscosity and inversely as the square of the diameter. Due to the fact that the internal surface of the pipe, even when new, will have an appreciable roughness, it is believed that the pressure will vary at a greater power of the velocity than one, this is borne out by Preston who, in his experiments, found that the velocity exponent varied from 1.0 to 1.1 with a fair average of 1.06.

The pressure required due to an increase in viscosity seems to increase directly as the first power of the viscosity. While it may be found by future work that this value of the viscosity exponent is not absolutely correct, yet, for the present, it must be accepted as such. The exponent of the diameter seems to decrease from 2.0 as given in the theoretical formula to an actual value of about 1.85. Therefore, formula I will

TABLE I.
FLOW OF OILS THROUGH STANDARD IRON PIPES.
PIPE SIZE

		1"		1½"		2"		3"		4"		6"		8"		10"		12"	
		C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P	C	P
100 secs. Saybolt.		5	60	5	12	10	10	25	10	50	5	100	3	300	3	400	3	500	2
		10	155	10	30	20	25	50	20	100	14	200	6	600	10	800	6	1000	5
		15	280	15	50	30	45	75	35	150	27	300	13	900	21	1200	12	1500	8
		20	475	20	75	40	75	100	50	200	50	400	20	1200	35	1600	20	2000	14
		25	725	30	135	50	120	125	85	250	80	600	40	1500	53	2000	31	2500	23
		30	1100	40	230	60	170	150	120	300	110	800	70	1800	72	2400	43	3000	34
				50	360	70	230	175	165	350	140	1000	105	2100	93	2800	57	3500	37
250 secs. Saybolt.		2½	105	5	40	5	20	20	10	50	8	100	3	300	4	400	4	400	2
		5	215	10	85	10	40	40	22	100	18	200	8	600	13	800	9	800	4
		7½	315	15	125	15	60	60	35	150	40	300	15	900	27	1200	17	1200	7
		10	420	20	160	20	80	80	50	200	72	400	25	1200	45	1600	27	1600	11
		12½	530	25	200	30	105	100	85	250	105	600	52	1500	67	2000	40	2000	19
		15	640	30	245	40	145	120	125	300	135	800	90	1800	92	2400	55	2500	29
		20	850	35	300	50	200	140	175	350	175	1000	135	2100	120	2800	75	3000	43
900 secs. Saybolt.		1	150	5	165	5	55	10	20	20	13	75	12	200	11	250	5	300	2
		2	290	10	330	10	110	20	45	40	25	150	25	400	24	500	11	600	5
		3	430	15	500	15	165	30	66	60	40	225	40	600	38	750	19	900	9
		4	570	20	660	20	220	40	88	80	55	300	55	800	54	1000	26	1200	12
		5	715	25	815	30	330	50	110	100	70	400	70	1000	70	1250	35	1500	16
		6	860	30	985	40	445	60	135	120	90	500	90	1200	86	1500	45	1800	20
16000 secs. Saybolt.						½	80	2	65	5	60	10	25	20	17	40	15	75	13
						1	160	4	130	10	120	20	55	40	35	80	30	150	26
						1½	240	6	205	15	180	30	80	60	55	120	48	225	40
						2	310	8	270	20	245	40	110	80	75	160	65	300	54
						2½	380	10	340	25	305	50	135	100	95	200	80	400	67
						3	450	12	400	30	375	60	160	120	120	250	100	500	85

C = Capacity in Barrels of 42 gal. per hour.

P = Pressure required to overcome friction head in lbs. per sq. in. per mile of pipe.

TABLE II.
FLOW OF LUBRICATING OILS THROUGH STANDARD IRON PIPES. REQUIRED PRESSURE PER 100 FT. OF PIPE AT GIVEN DISCHARGE.

		½"		¾"		1"		1¼"		1½"	
		Cap. gal. min.	Pres. lbs. sq. in.	Cap. gal. min.	Pres. lbs. sq. in	Cap. gal. min.	Pres. lbs sq.in.	Cap. gal. min.	Pres. lbs. sq.in	Cap. gal. min.	Pres. lbs. sq.in.
20 degrees Baume Gravity.	200 secs. Saybolt.	2	12	4	8	5	4	5	1	10	1
		4	25	8	17	10	8	10	3	20	3
		6	39	12	32	15	14	20	6	30	6
		8	53	16	52	20	23	30	13	40	10
		10	84	20	76	25	34	40	21	50	15
	300 secs. Saybolt	2	18	4	12	5	6	5	2	10	2
		4	38	8	26	10	12	10	4	20	5
		6	59	12	40	15	19	20	9	30	7
		8	81	16	63	20	28	30	16	40	12
		10	101	20	92	25	40	40	26	50	18
	400 secs. Saybolt	2	24	4	17	5	8	5	3	10	3
		4	50	8	35	10	17	10	6	20	6
		6	78	12	54	15	26	20	12	30	10
		8	107	16	75	20	35	30	19	40	15
		10	135	20	102	25	46	40	29	50	21
	500 secs. Saybolt	2	30	4	21	5	10	5	3	10	4
		4	63	8	43	10	21	10	7	20	8
		6	98	12	67	15	32	20	15	30	12
		8	135	16	91	20	43	30	22	40	17
		10	169	20	113	25	52	40	32	50	23
	600 secs. Saybolt	2	36	4	25	5	12	5	4	10	5
		4	76	8	52	10	25	10	8	20	10
		6	118	12	81	15	39	20	18	30	15
		8	162	16	110	20	52	30	27	40	20
		10	204	20	140	25	67	40	35	50	25

take the following form when applied to large pipes carrying viscous oil.

$$P = \frac{Vel.^{1.06} \times Vis. \times L}{C \times Dia.^{1.85}} \qquad VI.$$

In which the units are the same as given for formula V and C has a value of about 18.

The results given in table I were derived from actual tests and were not calculated from the formulae, yet, it will be found that they check the formulae reasonably close with the exception of those values for the two-inch pipe. Because of the conditions under which the tests on the two-inch pipe were made it is believed that the values given by the formulae will be more nearly correct than those set forth in the table. Your attention is here directed to the fact that the discharge as given by those figures for the oils of 100 secs. and 250 secs. Saybolt viscosity is taking place at turbulent flow while those for 900 secs. and 16000 secs. are for stream line flow.

The results as given in table II have been derived from formulae IV, V and VI, and while they may not possess the accuracy that should be desired, they are offered to relieve the reader from the necessity for making calculations to determine the size, pressure and quantity, particularly when applied to lubricating oils. Although a gravity of 20 degrees Baume was used in making these calculations the values will hold approximately true for any other gravity, providing the oils are of the same viscosity.

While it is felt that the above formulae cover in a general way the factors that affect the flow of a viscous fluid like oil, complete confidence should not be placed in the values of the numerous constants and exponents until they have been checked by many investigators working over a wide range of pipe sizes and viscosities. The engineer who is called upon to investigate a proposed pipe line installation may use the formulae as given in this article, but where possible he should check it with the results as given by an existing line that conforms to the conditions of his problem.

NOTE

Because of lack of space we have not been able to conclude the article on cement mill lubrication in this issue.

Lubrication of Pneumatic Tools

The name pneumatic tools applies to that class of portable, self-contained motor tools operated by compressed air. Pneumatic tools are sturdy little machines and will stand a lot of abuse. It is well that they will, however, for it is doubtful if any machines are handled more carelessly or roughly than these. This lack of proper attention, no doubt, is largely due to the fact that the rugged exterior appearance conveys a false impression of the intricate mechanism beneath. A study of the accompanying illustrations will reveal that pneumatic tools contain a number of more or less delicate parts.

In order to obtain a full measure of service from pneumatic tools and eliminate the necessity for repairs, it is of paramount importance that they be handled carefully and also kept clean and well lubricated with a high-grade lubricant. The working parts of pneumatic tools are accurately and closely fitted. If their lubrication is neglected these fine pieces of machinery wear rapidly and in a short time refuse to work.

There are a number of factors which make the lubrication of pneumatic tools difficult.

As we explained in the article on the lubrication of compressed air machinery appearing in the June number of LUBRICATION, the air passing through the tools expands and absorbs heat from its surroundings. Unless the air is preheated or the tool is operating in a very warm atmosphere, the expansion temperature may run very low. There is always a tendency for lubricants to congeal in the presence of cold, and unless they are manufactured for low-temperature conditions they may become sticky or stringy and greatly impede the operation of the machine.

In addition to the moisture carried into pneumatic tools by the air, some tools, notably water drills, are exposed to water leakage. As a result conditions in the cylinders are somewhat similar to those met with in the cylinders of pumps. In the case of mine drills the water leaking into the cylinder frequently contains an appreciable percentage of acid.

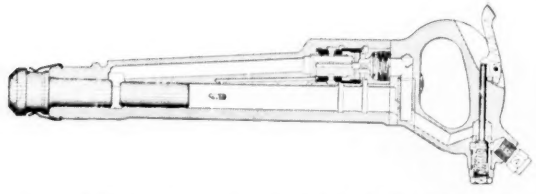
There is bound to be some little dust contained in the air carried into the cylinders of pneumatic tools. Further, the moisture in the air tends to corrode the transmission pipes and storage tanks with the result that some small particles of rust are carried along by the air. Particles of rubber from the air hose and gaskets may find their way with the other foreign matter into the air passages and cylinders and greatly interfere with the free operation of the tool. Dust, rust or rubber cannot be classed as lubricants and should be kept out of the tool by means of a fine wire strainer inserted in the inlet pipe.

Not all foreign matter which gets into the cylinders and valves of pneumatic tools is carried in with the air. Unless care is exercised a great deal may be fed in with the lubricant. We have known cases where the lubricant for pneumatic rock drills was kept in an open can near the drills. A great deal of dust and grit naturally fell into the can with the result that the drills were being "lubricated" with an abrasive compound.

In selecting lubricants for pneumatic tools, judgment should always be used as there are some tools, or portions of them, that require

A "JACK HAMMER"

a light oil while others work most successfully with grease. The lubricant most suitable for any particular pneumatic tool will vary with the type of tool, the nature of the work, the condition of the air and the state of the atmosphere. Generally speaking, the heavier tools require the heaviest lubricants, slow moving tools requiring a heavier lubricant than those operating at high speed. Heavy lubricants are necessary for use on tools using preheated air or those exposed to high temperatures.

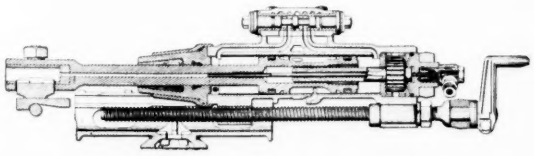


A RIVETING HAMMER. VALVE SHOWN IN SOLID BLACK

Tools of the trunk-piston and rotary types are commonly lubricated with a light grease, while the high-speed, hammer types such as riveting hammers, under average conditions of operation are most successfully lubricated with a light oil of about 100-150 seconds viscosity Saybolt at 100 degrees F. Tools such as reciprocating drills are provided with grease chambers which are filled by means of a grease gun and from which the grease slowly exudes into the cylinders. One charge of grease if suitable should last several weeks. The gears, crankshafts and pistons of rotary tools all operate in a bath of grease, new applications of which are necessary only after long periods of time. The high-speed tools are lubricated with oil by means of a squirt can. As there is a tendency on the part of the exhausting air to carry a light oil out with it, tools of this kind should receive a few drops of oil every hour or so.

Oils used upon pneumatic tools should have a low cold test and greases to be successful must be manufactured from low cold test oils. In addition, pneumatic-tool lubricants should possess enough body to prevent metal contact and friction, but if they are too heavy for the mechanical conditions they tend to impede the action of the tools.

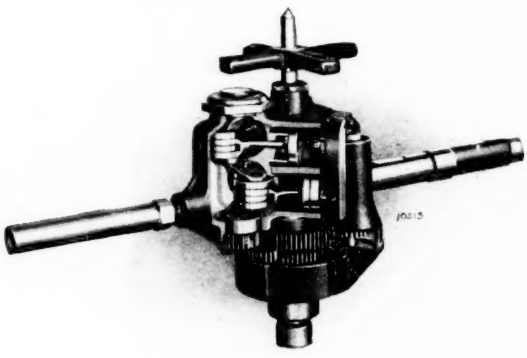
The operating efficiency of pneumatic tools will be greatly enhanced if they are frequently



A RECIPROCATING ROCK DRILL WITH WATER ATTACHMENT

cleaned. The smaller tools may be cleaned by submerging them in a bath of benzine or gasoline for a few hours, and then blowing them out under pressure. This dislodges any accumulations which may have built up in the tool. After a tool has been cleaned the working parts always should be lubricated thoroughly with the proper lubricant before the tool is put to work again.

Such small quantities of lubricants are used in pneumatic tools, and the shut-downs and depreciation resulting from the use of an unsuitable lubricant may cause such a large loss of money that a small difference of price between the best lubricant and a poor one should never be considered in purchasing an air-tool lubricant.



A ROTARY DRILL